Chapter 10. HYDRAULICS OF OVERLAND FLOW

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10.1 Introduction

Proper identification of hydraulic parameters is essential for the operation of other WEPP model components. Routing of surface runoff, which is described in Chapter 4, requires use of appropriate friction coefficients. Accurate hydraulic estimates are also needed for the erosion model component outlined in Chapter 11.

The Darcy-Weisbach equation is widely used to describe flow characteristics. Under uniform flow conditions, the Darcy-Weisbach friction coefficient, f, is given as (Chow, 1959)

$$f = \frac{8gRS}{V^2} \qquad \text{[10.1.1]}$$

where g is acceleration due to gravity ($m{\cdot}s^{-2}$), R is hydraulic radius (m), S is average slope, and V is flow velocity ($m{\cdot}s^{-1}$). The Darcy-Weisbach friction coefficient is a dimensionless parameter. Equations used to predict hydraulic coefficients in the WEPP model are presented below. Separate estimates of Darcy-Weisbach friction coefficients are made for rill and interrill areas. A total equivalent friction coefficient for cropland, f_e, is then computed as an area weighted average of the rill and interrill areas using the relationship

$$f_e = f_r \, A_r + f_i(1 - A_r) \qquad \text{[10.1.2]}$$

where f_r is the total friction coefficient in the rill, f_i is the total friction coefficient for the interrill region, and A_r is the fraction of the total area in rills.

10.2 Roughness Coefficients for Cropland Rills

Shear stress in rills is partitioned into two parts; one part that acts on the soil to cause detachment and another portion that acts on exposed residue or other surface cover and thus is not active in terms of soil detachment. The portion of the shear stress which acts on the soil and causes erosion is proportional to the ratio of the friction coefficient for the soil to the total friction coefficient (soil plus cover). If cover exists in the rill, the portion of total shear which acts on the soil will only be a fraction of the total shear stress in the rill. The total friction coefficient for rill areas, f_r is given as

$$f_r = f_{sr} + f_{cr} + f_{live} \qquad \text{[10.2.1]}$$

where f_{sr} is the friction coefficient for rill surface roughness, f_{cr} is the friction coefficient for rill surface residue, and f_{live} is the friction coefficient for living plants which act to slow runoff.

Friction coefficients for rill surface roughness were measured at 11 sites located throughout the eastern United States (Gilley et al., 1990). The experimental data were used to develop the following equation for estimating f_{sr}

$$f_{sr} = 1.11 \qquad \text{[10.2.2]}$$

A laboratory flume was employed to identify friction coefficients induced by surface residue (Gilley et al., 1991). The following equation for predicting f_{cr} was developed from the laboratory data

$$f_{cr} = 4.5 \, r_c^{1.55} \qquad \text{[10.2.3]}$$

where r_c is the fraction of the rill covered by residue material.

Values of f_{live} were obtained from the literature using data for closely spaced crops including alfalfa, grasses and small grains (Cox and Palmer, 1948; Ree and Palmer, 1949; Ree and Crow, 1977; and Ree et al., 1977). The maximum value of f_{live} (f_{livmx}) assumed for alfalfa and grasses was 12. A friction coefficient of 3 was assumed for wheat. A linear function was assigned based upon the canopy height of the plant, *canhgt*, compared to its maximum height, *hmax*:

$$f_{live} = (canhgt/hmax) \, f_{livmx} \qquad \text{[10.2.4]}$$

Roughness coefficients for row crops other than wheat were found to be negligible by Gilley and Kottwitz (1994).

10.3 Roughness Coefficients for Cropland Interrill Areas

Interrill surface roughness, surface residue cover, standing plant material, and gravel and cobble material may all influence the total friction coefficient for the interrill area, f_i, since

$$f_i = f_{si} + f_{ci} + f_{bi} + f_{live} \qquad \text{[10.3.1]}$$

where f_{si} is the friction coefficient for interrill surface roughness, f_{ci} is the friction coefficient for interrill surface cover, f_{bi} is the friction coefficient for a smooth bare soil, and f_{live} is the friction coefficient for living plants as defined earlier.

Interrill form roughness elements are primarily affected by the type of tillage operation which is performed and the cumulative rainfall occurring since tillage (Zobeck and Onstad, 1987). Form roughness elements may be quite large compared to flow depth on interrill areas. Finkner (1988) related form roughness elements to friction coefficients using the relationships

$$f_{si} = 0.500 \, f_o^{1.13} \, \exp^{-3.09(1.0 - r_i)} - f_{bi} \qquad \text{[10.3.2]}$$

where

$$f_o = \exp^{3.02 - 5.04 \exp^{(-161 \, r_o)}} \qquad \text{[10.3.3]}$$

and r_o is the initial random roughness of a freshly tilled soil (m), r_i is the ratio of random roughness at some later time to r_o, and f_o is the friction factor for a freshly tilled surface in the absence of cover.

The friction coefficient for interrill surface cover, f_{ci}, is given by

$$f_{ci} = 14.5 \, i_c^{1.55} \qquad \text{[10.3.4]}$$

where i_c is the fraction of the interrill area covered by nonmoveable residue. The above equation was developed using laboratory data obtained by Gilley et al. (1991). The friction coefficient for a smooth bare soil on an interrill area, f_{bi}, is represented as

$$f_{bi} = 4.07 \qquad \text{[10.3.5]}$$

Eq. [10.2.4] is used to compute the friction coefficient due to living plants, f_{live}.

10.4 Roughness Coefficient for Rangeland Rills

Shear stress in rangeland rills is partitioned into two parts, one part acts on the soil to cause detachment and another portion acts on exposed litter, rocks or other surface cover and thus is not active in soil detachment. The portion of the shear stress which acts on the soil and causes erosion is proportional to the ratio of the friction coefficient for the soil to the total friction coefficient (soil plus cover). If cover exists in the rill, the portion of total shear which acts on the soil will only be a fraction of total shear stress in the rill. The total friction coefficient for rangeland rills, f_{rr}, is given as

$$f_{rr} = f_{rs} + f_{ro} + f_{cs} - 15.87$$ [10.4.1]

where f_{rs} is the roughness coefficient for soil induced roughness, f_{ro} is the roughness coefficient for random roughness, and f_{cs} is the roughness coefficient for surface cover in the rill. If the value of f_{rr} is less than the value of f_{rs}, f_{rr} is set equal to f_{rs}.

The friction coefficient for grain roughness of the soil is assumed to be

$$f_{rs} = 1.11$$ [10.4.2]

The equation used to estimate the friction coefficient for random roughness (f_{ro}) in a rill is given as

$$f_{ro} = 42.76 \, (1.0 - e^{(-77.3 r_r)})$$ [10.4.3]

where r_r is random roughness (m) of the rangeland rill area.

The friction coefficient associated with surface cover for rills is represented as

$$f_{cs} = f_{rkr} + f_{ltr} + f_{pbr}$$ [10.4.4]

where f_{rkr} is the friction coefficient caused by gravel, rocks and stones in the rills, f_{ltr} is the friction coefficient associated with litter and organic residue in the rills, and f_{pbr} is the friction coefficient associated with plant stems, leaves, and cryptogam surface cover in the rills. The model does not estimate the fraction of litter that is detached and transported by overland flow. Litter is assumed to be nonmoveable and the model does not estimate the formation or destruction of litter debris dams. Gilley et al. (1992) conducted a laboratory study to measure friction coefficients for gravel and cobble surfaces. The following equation for estimating f_{rkr} was developed from the laboratory data

$$f_{rkr} = 1.85 \, r_{rock}$$ [10.4.5]

where r_{rock} is the fraction of the rill surface covered by gravel and cobble material.

Weltz et al. (1992) used computer optimization techniques to identify friction coefficients using the rising limb of runoff hydrographs obtained from rangeland plots. Their optimization data were used to develop the following equation for estimating f_{ltr}

$$f_{ltr} = 113.73 \, r_c^{3.0}$$ [10.4.6]

where r_c is the fraction of the rill surface covered by litter and organic residue.

The equation used to estimate the friction coefficient attributed to plant stems and cryptogam surface cover is (Weltz et al., 1992):

$$f_{pbr} = 0.5\,(125.91\,(B_{ar} + C_{ccr})^{0.8})$$ [10.4.7]

where B_{ar} is the fraction of the rill surface covered by plant stems, and C_{ccr} is the fraction of the rill surface covered by cryptogams.

10.5 Roughness Coefficients for Rangeland Interrill Areas

The friction coefficient for interrill rangeland areas, f_{ir}, is calculated as

$$f_{ir} = \frac{f_{bi} + f_{ro} + f_{ri} - 15.87}{0.65}$$ [10.5.1]

where f_{bi} is the roughness coefficient for soil grain roughness, f_{ro} is the roughness coefficient for random roughness, and f_{ri} is the roughness coefficient for surface cover. The friction coefficient for random roughness is calculated in a similar manner for rill and interrill areas (Eq. [10.4.3]). The friction coefficient due to soil grain roughness on interrill areas is calculated using

$$f_{bi} = 4.07$$ [10.5.2]

which is based on results of a laboratory study of Gilley et al. (1991). If the value computed for f_{ir} using Eq. [10.5.1] is less than f_{bi}, then f_{ir} is set equal to f_{bi} within the WEPP model.

The friction coefficient for surface cover on interrill areas is calculated as

$$f_{ri} = f_{rki} + f_{lti} + f_{pbi}$$ [10.5.3]

where f_{rki} is the friction coefficient associated with gravel, rocks, and stones on the interrill area, f_{lti} is the friction coefficient caused by litter and organic residue on the interrill area, and f_{pbi} is the friction coefficient associated with plant stems and cryptogam surface cover on the interrill area.

Friction coefficients associated with gravel, rocks and stones, and litter and organic residue are estimated using the following equations:

$$f_{rki} = 1.847\,i_{rock}$$ [10.5.4]

$$f_{lti} = 113.73\,i_c^{3.0}$$ [10.5.5]

where i_{rock} is the fraction of the interrill area covered by gravel and cobble material, and i_c is the fraction of the interrill area covered by litter and organic residue.

Weltz et al. (1992) used optimization procedures to develop the following equation for estimating f_{pbi}

$$f_{pbi} = 38.95\,C_c^{0.8} + 125.91\,(B_{ai} + C_{cci})^{0.8}$$ [10.5.6]

where C_c is the fraction of total canopy cover, B_{ai} is the fraction of the interrill area covered by plant stems, and C_{cci} is the fraction of the interrill surface covered by cryptogams.

The model does not predict the fraction of plant material that may be transported by overland flow or the formation and destruction of debris dams. A constant gravel and cobble cover is assumed. The formation of erosion pavement (increase in rock cover) is not considered.

10.6 Temporal Variations in Roughness Coefficients

The fraction of the surface covered by crop residue on croplands, or litter and organic residue on rangelands, affects rill or interrill friction coefficients. Tillage, residue decomposition, harvesting, grazing or burning may reduce vegetative cover. Friction coefficients may also be influenced by varying canopy cover, canopy height, and basal plant cover.

Friction coefficients on interrill areas may be significantly affected by tillage induced soil roughness. Soil roughness parameters may vary substantially with different tillage implements. Rainfall may also cause reductions in friction coefficients. Mechanical disturbance of the soil on rangeland is currently not an option considered by the model.

10.7 Rill Density and Width

Gilley et al. (1990) measured rill density, rill flow rates and rill widths during rainfall simulation tests conducted at 11 sites located throughout the eastern United States. They suggested use of a rill density approximation of 1.0 rills/m. Flow rates are assumed to be the same in each rill.

If rainfall excess and rill density are known, rill flow rate, Q_e, can be calculated. Rill width, w, can then be estimated using the following regression equation developed by Gilley et al. (1990)

$$w = 1.13 \, Q_e^{0.303} \qquad \text{[10.7.1]}$$

The effects on rill geometry of soil layers with varying density are not considered in the model.

10.8 References

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10.9 List of Symbols

Symbol	Definition	Units	Variable
A_r	fraction of the total area in rills	-	rillar
B_{ai}	fraction of basal plant cover on interrill rangeland areas	-	bascov*fbasi
B_{ar}	fraction of basal plant cover in rangeland rills	-	bascov*fbasr
C_c	fraction of total canopy cover on rangeland areas	-	cancov
C_{cci}	fraction of cryptogam cover on interrill rangeland areas	-	crycov*frcyi
C_{ccr}	fraction of cryptogam cover in rangeland rills	-	crycov*fcryr
canhgt	canopy height of the plant	m	canhgt
f	Darcy-Weisbach friction coefficient	-	-
f_{bi}	friction coefficient for a smooth, bare soil on an interrill area	-	inrsco
f_{ci}	friction coefficient for interrill surface cover on a cropland area	-	inrfco
f_{cr}	friction coefficient for rill surface residue on a cropland area	-	frccov
f_{cs}	friction coefficient for rill surface cover on a rangeland area	-	frccov
f_e	total equivalent friction coefficient	-	frcteq
f_i	total friction coefficient for the interrill area on croplands	-	inrfto
f_{ir}	total friction coefficient for the interrill area on rangelands	-	inrfto
f_{live}	friction coefficient due to living plants on cropland	-	frlive
f_{livmx}	maximum value of f_{live}	-	flivmx
f_{lti}	friction coefficient for interrill litter and organic residue on rangelands	-	frires
f_{ltr}	friction coefficient for rill litter and organic residue on rangelands	-	frrres
f_o	friction coefficient for form roughness on a cropland interrill area	-	inrfo
f_{pbi}	friction coefficient for basal cover on a rangeland interrill area	-	fribas
f_{pbr}	friction coefficient for basal cover in a rangeland rill	-	frrbas
f_r	total friction coefficient in a cropland rill	-	frctrl
f_{ri}	friction coefficient for surface cover on a rangeland interrill area	-	inrfco
f_{rki}	friction coefficient for gravel, rocks and stones on an interrill rangeland area	-	frirok
f_{rkr}	friction coefficient for gravel, rocks and stones in a rangeland rill	-	frirok
f_{ro}	friction coefficient for random roughness on rangelands	-	inrfro
f_{rr}	total friction coefficient in a rangeland rill	-	frctrl
f_{rs}	friction coefficient for soil in a rangeland rill	-	frcsol
f_{si}	friction coefficient for interrill surface roughness	-	inrfro
f_{sr}	friction coefficient for rill surface roughness	-	frcsol
g	acceleration due to gravity	$m{\cdot}s^{-2}$	accgav
hmax	maximum plant height	m	hmax

i_c	fraction of the interrill area covered by nonmovable residue material	-	rescov*fresi
i_{rock}	fraction of the interrill area covered by gravel, rocks and stones on rangelands	-	rokcov*froki
Q_e	rill flow discharge	$m^3 \cdot s^{-1}$	qshear
r_c	fraction of the rill covered by nonmovable residue material	-	rescov*fresr
r_i	ratio of random roughness at some later time to initial random roughness	-	rrrinr
r_{rock}	fraction of the rill surface covered by gravel, rocks and stones on rangelands	-	rokcov*frokr
r_o	initial random roughness of a freshly tilled surface	m	rroinr
r_r	random roughness value on rangelands	m	rrough
R	hydraulic radius	m	hydrad
S	average slope	-	-
V	flow velocity	$m \cdot s^{-1}$	-
w	rill width	m	width